Dusty torus formation by anisotropic radiative pressure feedback of active galactic nuclei

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ABSTRACT

The feedback by active galactic nuclei (AGNs) is significant for the formation and evolution of galaxies. It has been realized that the radiative pressure feedback could be an efficient mechanism due to the existence of dust. In this Letter, we discuss the effect of anisotropic radiative pressure, which is inevitable if the UV/optical emission arises from an accretion disk. The distribution of dusty gas should be also anisotropic due to the influence of the anisotropic disk radiation, i.e. the dust in the face-on direction of an accretion disk can be blown out relatively more easily, whereas the dust can survive in the edge-on direction. This result can explain the presence of some obscured AGNs with high Eddington ratios and can also quantitatively reproduce the observed decreasing fraction of type 2 AGNs with increasing luminosity. A sequence of AGN formation and evolution is also proposed, within the context of the formation, evolution and exhaustion of the dusty torus. Our model predicts the existence of bright AGNs with dusty tori, but without broad line regions. Finally we discuss the implications of the anisotropic radiation for the calculations of luminosity functions and radiation efficiencies of AGNs.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — X-rays: galaxies

1. Introduction

Various correlations over the past decade have been found between the mass of black holes in the center of galaxies ($M_{\rm BH}$) and the properties of host galaxies, e.g. the velocity dispersion σ of the galaxy's bulge ($M_{\rm BH}$-σ relation, Tremaine et al. 2002), the mass of the

galaxy's bulge $M_{\rm bulge}$ ($M_{\rm BH}$-$M_{\rm bulge}$ relation, Marconi & Hunt 2003), and the concentration of the spheroid (Graham & Driver 2007). These results indicate that supermassive black holes play a fundamental role in the formation and evolution of galaxies (Silk & Rees 1998; Fabian et al. 2002; Di Matteo et al. 2005; Menci et al. 2008). Numerous models have been proposed to explain the observed correlations. The feedback by active galactic nuclei (AGNs) is promising to connect the properties at quite different scales (e.g. King 2003; Murray et al. 2005; Springel et al. 2005; Shin et al. 2010).

The form of feedback could be either energy injection or momentum injection. Among various mechanisms of feedback, radiative pressure could be an efficient one, though it is only important when the luminosity of the central source is near the Eddington luminosity, i.e. $L_{\rm Edd} = 4\pi G m_{\rm p} c M_{\rm BH}/\sigma_{\rm T}$, where G is the gravitational constant, $m_{\rm p}$ is the proton mass, c is the light speed, and $\sigma_{\rm T}$ is the cross-section for Thomson scattering. However, the existence of dust could remarkably amplify the effective cross-section and then reduce the required luminosity that can balance the gravitational force of the central black hole. If the effective cross-section of dusty gas is $\sigma_{\rm eff} = A\sigma_{\rm T}$, where $A > 1$ is the boost factor, the effective Eddington luminosity is simply lower than $L_{\rm Edd}$ by a factor of A. Thus the feedback by radiative pressure can be important even if the real luminosity is sub-Eddington. Therefore, the dusty gas will be cleared out by the accreting black hole in a very short time ($\lesssim 10^5$ yr) if the luminosity of the accreting black hole is high enough (Chang et al. 1987; Murray et al. 2005; Fabian et al. 2002, 2006; Raimundo et al. 2010).

Although the importance of radiative pressure has been discussed by several authors, the effect of anisotropic radiation has so far not been taken into account. As we will show in this Letter, including the effect of anisotropic radiative pressure is critical to understanding several observational results. Actually, anisotropic radiation is a natural result if the emitting region is an accretion disk, especially for the ultraviolet and optical emission, which are thought as the evident signal of an accretion disk around a supermassive black hole.

In §2, we investigate the effects of anisotropic radiative pressure on the distribution of dust. In §3, we utilize the anisotropic radiative pressure to explain the presence of some AGNs with high Eddington ratios and high column densities. As a further quantitative test, we reproduce the observed fraction of type 2 AGNs using the model proposed in this Letter in §4. In §5, we discuss the implications of the anisotropic radiation and give our conclusions.

2. Anisotropic radiative pressure

The big blue bump in ultraviolet to optical bands of the spectral energy distribution of AGNs dominates the total output of AGNs and is thought as the emission from an accretion disk around a supermassive black hole, though the observational evidence is still not very unambiguous (e.g. Shang et al. 2005; Kishimoto et al. 2008). The UV/optical opacity also dominates the overall opacity in the dust. As a result, the anisotropic disk UV/optical emission must have significant impacts on the global properties of the dusty structure around the accretion disk. For the standard accretion disk model, which is optically thick and geometrically thin, the optical depth is dominated by electron scattering in the inner part, which is the emitting region of ultraviolet and optical photons (Shakura & Sunyaev 1973). In this case, the emitting specific intensity I depends on the inclination angle $\mu = \cos\theta$, where θ is the angle between the line of sight and the normal of the accretion disk, as $I(\mu) \propto (1+2\mu)$ (Chandrasekhar 1960; Sunyaev & Titarchuk 1985). Therefore, the observed flux is

$$F(\mu) = \frac{L}{4\pi r^2}\frac{\mu I(\mu)}{\int_0^1 \mu I(\mu) d\mu} = \frac{6}{7}F_0\mu(1+2\mu), \tag{1}$$

where L is the total luminosity of the source, r is the distance between the observer and the source, and $F_0 = L/4\pi r^2$. Equation (1) is valid only if the optical depth is large enough, i.e. $\tau > 10$, which is well fulfilled in the inner region of the standard accretion disk model. In contrast to the anisotropic disk UV/optical continuum, the emitting region of X-ray is likely to be optically thin or a quasi-spherical corona, hence the X-ray emission should be nearly isotropic.

The relativistic effects can diminish the anisotropy of the photons from the innermost region of the accretion disk around a rapidly spinning black hole; for example, the edge-on flux can be effectively enhanced by the gravitational bending of the black hole. However, these effects are sensitive to the frequency of photons and the value of the spin of black holes in AGNs is still under debate (Volonteri et al. 2005; Wang et al. 2009; Shankar et al. 2009). In contrast, the flaring structure in the outer part of the accretion disk can shield the radiation from the inner part (Shakura & Sunyaev 1973), and therefore may partly cancel the gravitational bending effect and then enhance the anisotropy. Thus we temporarily ignore the above effects in this Letter for simplicity.

Since the radiation flux depends on the inclination angle, the effective Eddington luminosity should also be a function of the inclination angle. The equation of radial motion for the material under the influence of the anisotropic radiative pressure and the gravitational force of black hole is

$$\frac{dv}{dt} = \frac{\sigma_{\rm eff} F(\mu)}{m_{\rm p} c} - \frac{GM_{\rm BH}}{r^2}. \tag{2}$$

When the gravitational force is balanced by the radiative pressure, we obtain an equation of the critical angle θ_c

$$\cos\theta_{\mathrm{c}} = \frac{\sqrt{1+28/(3\lambda)}-1}{4}, \tag{3}$$

where the effective Eddington ratio $\lambda = AL/L_{\mathrm{Edd}}$.

We show the dependence of θ_c on λ in Figure 1 and the distribution of dust for different values of A and L/L_{Edd} in Figure 2. If $\lambda < 7/18$, there is no real root for equation (3), i.e., the radiative pressure is too weak to blow out the material in any direction. If $\lambda \geq 7/18$, then the matter between 0 and θ_c will be expelled by the radiative pressure. However, the matter distributed with $\theta > \theta_c$ will still be controlled by the gravitational force. We note that this critical value of λ is smaller than unity, which is the result of the anisotropic radiation, i.e., more energy is emitted towards $\mu = 1$. At the same time, even the luminosity is very high ($\lambda \sim 10$), there is still a considerable solid angle ($\sim$0.1) within which the dust could survive. In general, as the result of the anisotropic radiative pressure feedback, the distribution of dust is also anisotropic, i.e., the dust is expelled in the face-on direction of the accretion disk but still exists in the edge-on direction. Since gas is strongly coupled with dust by Coulomb force, scattering, and magnetic field (Chang et al. 1987; Scoville & Norman 1995; Murray et al. 2005), we expect the distribution of gas should be similar to that of dust.

As we will show in the next two sections, this anisotropic distribution of dusty gas is important for explaining several observational results.

3. Column density vs. Eddington ratio plane

In the isotropic radiative pressure model, it is predicted that there is a dividing line in the column density (N_{H}) vs. Eddington ratio (L/L_{Edd}) plane; at the right side of the plane, i.e. the Eddington ratio is high enough, the dusty gas could not be long-lived (e.g. see Figure 4 in Raimundo et al. 2010). However, the presence of obscured quasars is likely to contaminate the right side of the dividing line in the N_{H}-L/L_{Edd} plane (e.g. Brusa et al. 2005; Vignali et al. 2006; Polletta et al. 2008). Although the contamination may be explained as the absorption in the large scale of host galaxies, outflow or transient absorption (Raimundo et al. 2010), we propose that this discrepancy could be more naturally alleviated by the effect of anisotropic radiative pressure. As discussed in §2, even if the Eddington ratio is high, in the edge-on direction of the accretion disk, there still exists a region dominated by the gravitational force and therefore the dust could exist. If our line of sight happens to intersect this region, we will observe an obscured AGN. Therefore, there is no definite dividing line in the N_{H}-L/L_{Edd} plane. However, the probability of the presence of such a

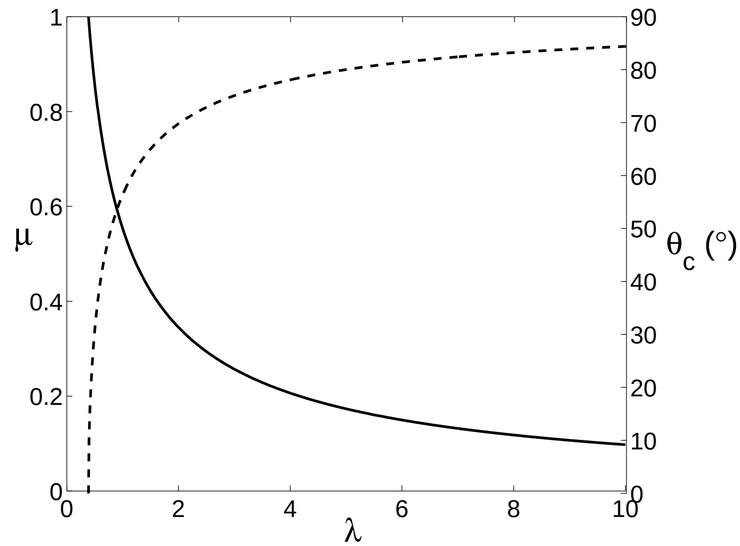

Fig. 1.— The critical angle $\mu = \cos\theta_{\rm c}$ as a function of $\lambda = AL/L_{\rm Edd}$.

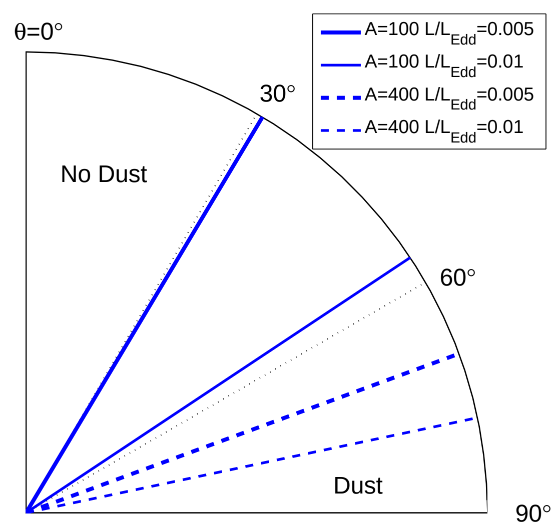

Fig. 2.— The section plan of the distribution of dust with different values of A and $L/L_{\rm Edd}$ in spherical coordinate. The lines are dividing planes with $\theta = \theta_c$.

high column density AGN decreases as the increase of Eddington ratio and thus the decrease of the solid angle occupied by dust (see Figure 1 and 2).

Figure 3 shows the probability of finding an obscured AGN in the $N_{\rm H}$-$L/L_{\rm Edd}$ plane. We adopt the relation between $N_{\rm H}$ and A obtained by Fabian et al. (2006). Since the value of the boost factor A is smaller for higher column density, it is more likely to find an obscured AGN with high $L/L_{\rm Edd}$ in the upper part of the $N_{\rm H}$-$L/L_{\rm Edd}$ plane. Although the probability decreases in the right part of the $N_{\rm H}$-$L/L_{\rm Edd}$ plane, there is still a considerable probability (at least 0.1$\sim$0.2) to find AGNs with high $N_{\rm H}$ in the forbidden region obtained by assuming isotropic radiation from an accreting black hole located at the center of an AGN.

This prediction is more consistent with the observed result shown in Figure 3. Note that the bolometric luminosity of the observed sample is estimated by the more isotropic X-ray luminosity and thus can be considered as the intrinsic one, or at least tracks the intrinsic one well (as we discussed in §2). Although the uncertainty of $L/L_{\rm Edd}$ is unlikely to qualitatively change the distribution of the observed sample, it is not straightforward to compare our prediction quantitatively in the $N_{\rm H} - L/L_{\rm Edd}$ plane due to the unknown underlying bias and intrinsic distributions of $L/L_{\rm Edd}$ and $N_{\rm H}$. Another closely related observed result, the decreasing fraction of type 2 AGNs with increasing luminosity, provides a good opportunity to test our scenario quantitatively. We will address this problem in the next section.

4. The fraction of Type 2 AGNs

In the unified model of AGNs, the classification is determined solely by the viewing angle between the observer and the symmetry axis of the dusty torus (Antonucci 1993). For type 1 AGNs, the broad line region (BLR) and the central engine are observed directly through the opening angle of the dusty torus, but they are obscured by the torus for type 2 AGNs. Thus, it is expected that the intrinsic properties of both type 1 and 2 AGNs are the same. However, with the fast growth of multi-wavelength surveys, it is found that the fraction of type 2 AGNs decreases with increasing luminosity (e.g, Ueda et al. 2003; Maiolino et al. 2007; Hasinger 2008). We propose here that the observed fraction of type 2 AGNs could be explained if we consider the effects of the anisotropic UV/optical radiation from the accretion disk. As we discussed in §2, dust could only exist in the region with $\theta_c < \theta < \pi/2$ and the covering factor of this region will decrease as the luminosity of the central source increases for the given black hole mass.

We adopt the fraction of type 2 AGNs obtained by Hasinger (2008), who compiled the largest AGNs sample (1290 AGNs) from several X-ray surveys (2-10 keV), combined the

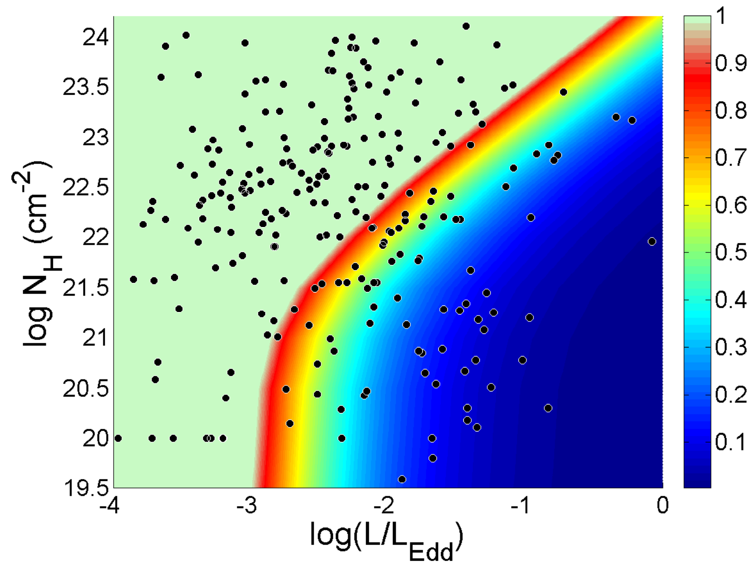

Fig. 3.— The probability, shown in color scale, of finding an obscured AGN in the $N_{\rm H}-L/L_{\rm Edd}$ plane considering the anisotropic radiative pressure. The data points (*black* circles) mark locations of AGNs on the $N_{\rm H}-L/L_{\rm Edd}$ plane, taken from Figure 4 in Raimundo et al. (2010) (the data points only with the upper limits of $N_{\rm H}$ are ignored).

optical and X-ray classifications, and then gave the most accurate estimate of the fraction of type 2 AGNs up to now.

For a realistic sample of AGNs, the observed luminosity is also correlated with the black hole mass. We simply parameterize this relation as $M \propto L^{\alpha}$; we then combine the normalization of this relation, the booster factor A, and the conversion factor between L and $L_{\rm X}$ (we assume $L \propto L_{\rm X}$, where $L_{\rm X}$ is the X-ray luminosity in 2-10 keV band) into a free parameter, the value of which is adjusted to match the observation data. If we identify the fraction of the solid angle covered by the dust as the fraction of type 2 AGNs (f_2), then $f_2 = \cos\theta_{\rm c}$ and f_2 is a function of $L_{\rm X}$ according to equation (3)

The real value of α of this sample is unclear. Thus we try several values of α in Figure 4, but do not treat it as a free parameter since we do not expect a single value of α could account for all AGNs in the sample. It seems that $\alpha \sim 0.6 - 0.7$ can well reproduce the observed fraction and a larger value of α is more appropriate in the low luminosity band. Actually, the fraction of type 2 AGNs could be overestimated in our model, especially in the low luminosity band, since the collapse of dust is not considered (see the discussion in §5). The value of α also depends on samples, which may explain the somewhat different trends of type 2 AGNs found in different samples (e.g. see the comparison in Hasinger 2008).

5. Discussion and conclusion

In this Letter, we have investigated the influence of the anisotropic radiation from the accretion disk on the distribution of dust in AGNs. The critical luminosity required to blow out the dusty gas is smaller than the standard Eddington luminosity (including the effects of dust), since more radiation is concentrated towards the face-on direction of the accretion disk. Therefore, there is a critical angle defining a permitted region where the dust could exist even the Eddington ratio is high. Thus, we obtained the probability of finding an obscured AGN in the $N_{\rm H}$-$L/L_{\rm Edd}$ plane, which is quantitatively consistent with observations. We further tested our model using the fraction of type 2 AGNs determined by X-ray surveys and found the decreasing trend of the fraction with increasing luminosity can be well explained.

Under our scenario, there should be an evolving sequence from type 2 AGNs to type 1 AGNs (Koulouridis et al. 2009), as illustrated in Figure 5. It is commonly believed that seed black holes must be formed before the AGN phase (Figure 5 (a)) (e.g. Lu et al. 2003; Hu et al. 2006). In the initial AGN phase, the dust produced by strong star formation process could shield the emission from AGNs from almost all directions (Figure 5 (b)); therefore in

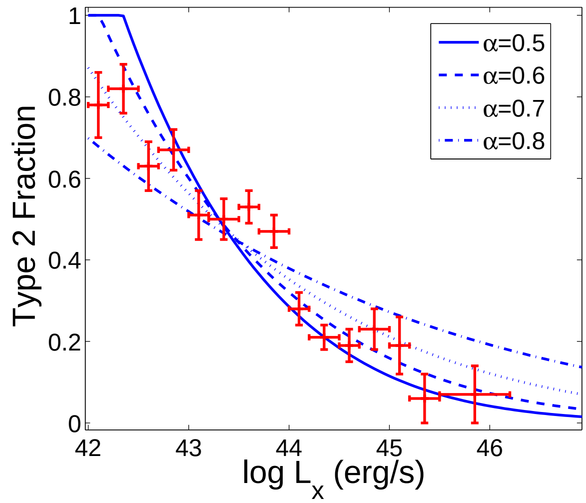

Fig. 4.— The fraction of type 2 AGNs as a function of X-ray luminosity $L_{\rm x}$ in 2-10 keV band. The data points with errors bars are taken from Hasinger (2008).

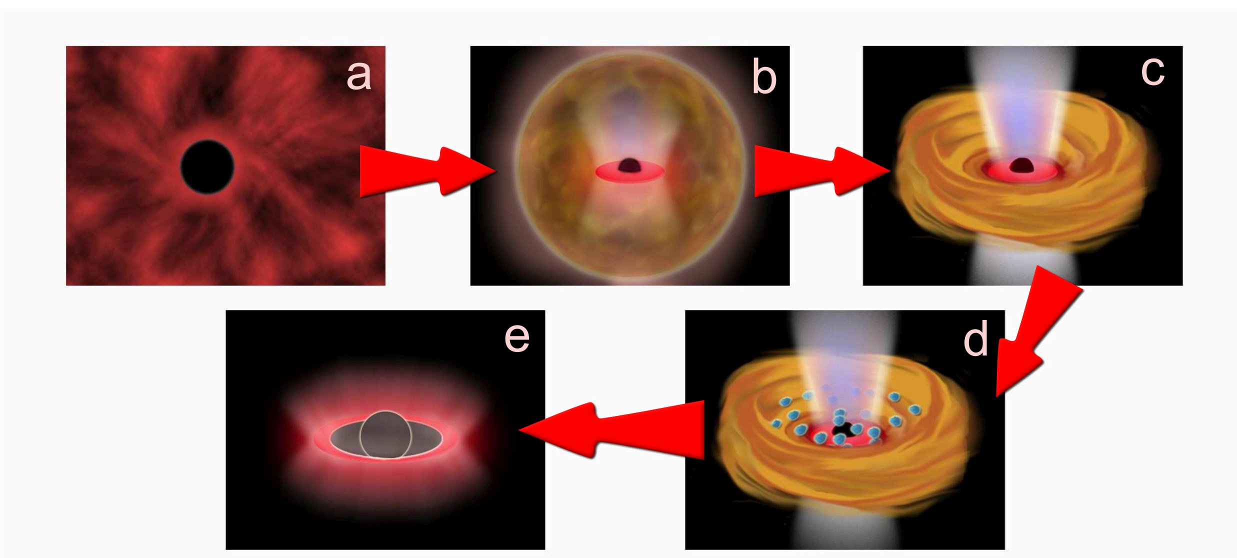

Fig. 5.— Illustration of the formation and evolution of AGNs. (*a*) The fast growth phase of a seed black hole. (*b*) The black hole and its accretion disk are embedded in a dusty ball. (*c*) The anisotropic radiative pressure blows out the dusty gas in the face-on direction of the accretion disk and results in a dusty torus. (*d*) The normal phase of an AGN with the inner structure, e.g. broad line region. (*e*) The dying phase of an AGN when its fuel is consumed out. See text for further explanations.

this phase most AGNs appear as type 2s. Subsequently, the feedback from AGNs begin to expel the dusty gas (Figure 5 (c)) and then the type 1 AGNs begin to dominate the bright population of AGNs, as shown in Figure 4. Therefore, there should be a significant increase in the fraction of type 2 AGNs with redshift, which is supported by recent observations (Hasinger 2008; Treister et al. 2010). As gas is strongly coupled with dust, both dust and gas should be blown out within the radiation cone. At this stage the AGN should have a dusty torus, but no BLR (Figure 5 (c)). Our model describes the physical process from stage (b) to stage (c) in Figure 5, and thus *predicts the existence of bright AGNs with dusty tori, but without BLRs*, e.g. weak line quasar (Fan et al. 1999; Plotkin et al. 2010). Subsequently the BLR is formed, as the dusty torus supplies the fuel to the accretion disk (Figure 5 (d)). As the fuel from the torus is gradually exhausted, both the torus and the BLR disappear at the end of the AGN activity (Figure 5 (e)), in qualitatively agreement with the results by Nicastro (2000), Laor (2003), Elitzur and Ho (2009), Zhang et al. (2009), and Zhu et al (2009); we will investigate quantitatively the effects of anisotropic radiative pressure on this evolutional scenario in a future work.

If the dusty torus could exist for a long time, there should be some supporting mechanism to maintain its thickness. However, this is still a controversial issue. Several models are proposed, e.g., random motion of clouds, radiative pressure, and magnetic field (see Krolik 2007 and references therein). Strictly speaking, the permitted region given by equation (3) is an upper limit for the height of the dusty torus. The real height of the torus could be smaller than this region if the support is not sufficient to make the dust fill this region, e.g., the disk wind may quench in low luminosity AGNs (Elitzur & Shlosman 2006). However, as shown in §4, the observed fraction of type 2 AGNs could be well explained by this simple model, which indicates that the support is likely to be sufficient in most cases. We must stress that this statement is only tentative. More realistic model of the torus is beyond the scope of this Letter and will be discussed in future works.

The covering factor of the dusty torus (or the fraction of type 2 AGNs) can be also inferred from the ratio between mid-IR to bolometric luminosity. Maiolino et al. (2007) and Treister et al. (2008) found that the covering factors determined by this method and X-ray surveys have the same trends with the bolometric luminosity, but the former is systematically higher. If the above result is real, this could be due to the missing Compton thick AGNs in X-ray surveys and well explained by our model, since the value of the boost factor A is smaller for Compton thick AGNs (large $N_{\rm H}$). However, the contribution from other components rather than the dusty torus can contaminate the mid-IR luminosity and further make the covering factor estimated in this way questionable (Rowan-Robinson et al. 2009; Mor et al. 2009). The inconsistency in different observations may also reveal the complex geometry of material responsible for absorptions in X-ray and mid-IR bands, which should be further

investigated using multi-wavelength data.

Our model is not in conflict with the receding torus model but actually complementary to that model (Lawrence 1991). Due to the unclear supporting mechanism and geometry of dust, the fraction of type 2 AGNs cannot be directly related to the variation of the inner radius of dust. The radiative pressure, as another constraint on the permitted region of dust, could link the opening angle of the dust (the fraction of type 2 AGNs) to the properties of the black hole more explicitly. Our model also predicts that the direction of the symmetry axis of the dust torus will be consistent with that of the normal of the accretion disk, but may be random relative to the direction of the host galaxy.

The anisotropic radiation could be important for the estimate of the intrinsic luminosity and then several properties of AGNs. For example, for an AGN observed with an inclination angle $\theta = 30^\circ$, by equation (1), the intrinsic luminosity is overestimated by a factor of two, if we calculate the luminosity using the observed flux assuming isotropic radiation. We will consider the effect of this bias on the calculations of luminosity function, radiation efficiency, and further black hole spin in future works.

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